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Statistical Analysis of Precipitation and Inundation Effects on Trees in Different Flooding Regimes.

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STATISTICAL ANALYSIS OF PRECIPITATION AND INUNDATION EFFECTS ON TREES IN DIFFERENT FLOODING REGIMES

by

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ABSTRACT

Although wetland trees show a relationship between growth and precipitation that can be used to reconstruct past climates they also show a relationship between growth and inundation which may be less helpful to climate modelers. Although inundation is directly related to precipitation in open stream channels, this may not be the case in impounded streams or in lake-side swamps or off-channel wetlands. In order to distinguish precipitation and inundation effects on growth, the effects of fluctuations in precipitation and inundation on bald cypress located at different elevations along lake-side swamp were examined. Upland trees were more influenced by variation in precipitation while trees closer to open water were found to be more influenced by the amount of inundation. Trees in middle elevation subjected to periodic flooding were not significantly influenced by either precipitation or inundation. The findings of the study have implications for future paleoclimate reconstructions where drainages have been most influenced by humans.

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I. Introduction

The possibility of reconstructing past climates by examining interannual variation in the width of tree rings arose out of studies in the arid environments of the southwestern United States (Douglas 1937). Trees in these areas typically grow in dry or well-drained soils, and since they experience little precipitation throughout the year there is a noticeable, positive relationship between tree growth and precipitation. The trees have a distinct but temporally limited growing season when they grow in response to precipitation (Douglas 1937, 1941). The use of dendrochronological records to reconstruct past southwestern U.S. climates has facilitated our understanding of the disappearance of the Anazasi in the late 1200s (Roberts 1996), the policy discussions of water allocation based on long term variation in flow of the Colorado River (Woodhouse *et al.* 2006), and in recognizing the frequency of drought in the southwest (Cook *et al.* 2004; Powell 2008).

Trees that grow well in swamps and other areas of standing water do not seem as likely to be affected by precipitation as trees in arid environments, but several studies (Stahle *et al.* 1985, Stahle and Cleveland 1995, Stahle *et* al. 1998, Galicki 2000, Chambers 2002) on bald cypress (*Taxodium distichum*) confirm the same positive relationship between growth and precipitation. For studies on trees in water-saturated soils, the correlation of precipitation and growth within a certain seasonal time frame was carried over from the idea of Southwestern arid environment studies that growing season defined precipitation limited growth. Trees in saturated soils might not have the same growing season as trees in arid regions, but they still exhibit sensitivity to climatic conditions and thus prove useful in reconstructing past climates. Similar to studies in the arid southwest, various climate-related phenomena have been analyzed using tree records from the humid eastern U.S. [drought conditions and loss of Jamestown and Roanoke colonies (Stahle 1998); and past rainfall (1000 years of Southeastern spring rainfall; Stahle and Cleaveland 1992)].

Several studies conducted on bald cypress have suggested that in addition to precipitation, inundation can also have a distinct effect on tree growth. When Reelfoot Lake, TN, was created by the New Madrid earthquake in 1811-1812, subsidence severely altered the hydrology of the area and bald cypress that had been along a Mississippi River tributary stream channel were then continually flooded. The trees in the new lake experienced a surge in growth for six years after the earthquake and resulting inundation, followed by a return to pre-earthquake growth levels (Stahle *et al.* 1992). A similar growth surge was seen in trees already in a permanently flooded area after an increase of approximately 60 cm in water level following the construction of a road; after fifteen years growth returned to pre-construction levels (Young et al. 1995).

It could be hard to tease apart the effects of inundation and precipitation. Within a stream channel, the height of the water is usually directly related to precipitation (Allan 1995). There are instances where that might not always be the case. Flood control dams put in place along a river generally affect the relationship of precipitation and inundation because the purpose of dam operations is to remove the extreme variation in stream flow that causes flooding downstream. These changes in hydrologic regime due to dam operations affect growth in trees with respect to both inundation and precipitation. Chambers (2002) examined the relationship between growth and both precipitation and inundation on trees above and below, and before and after closure of a flood control dam Sardis, in Batesville, MS. Below the dam, tree growth was directly related to precipitation before the dam was constructed, but no relationship was seen between growth and precipitation after the dam's closure. Since the dam was being managed for flood control, the pre-dam relationship between precipitation and inundation in the downstream channel had been removed. In trees above the dam (all as young as or younger than the dam) there was a relationship between growth and precipitation (r^2= 0.09; P= 0.029), but Chambers found no relationship between growth and length of inundation (r^2 = 0.0026; P = 0.26). Chambers shows that duration of inundation was not a good predictor of growth, but also that there is a difference between precipitation and inundation effects.

The exact mechanism of how precipitation increases growth in trees with continuous access to water is not known but certain authors have addressed this conundrum (Davidson *et al.* 2006; Galicki 2002, Young *et al.* 1995; Keeley 1979). Precipitation could be increasing growth by increasing the nutrient load either through increased run off of sediments (Galicki 2002) or movement of water through the root zone (Davidson *et al.* 2006). In Davidson *et al.* (2006), the idea of precipitation-induced groundwater chemistry changes was studied by examining chemical constituents in a series of piezometer nests at different elevations in the lake. Davidson *et al.* (2006) conducted their study in Sky Lake, a perched hydrologic system near Belzoni, MS, where the lake and surface water lie above the groundwater, allowing the surface water to flow into the groundwater depending on how deeply the particular locations are inundated (Mitsch and Gosselink 1993). Davidson *et al.* found that as water in the lake-side swamp exceeded a depth of one meter or more above the ground surface there was a flushing of water from the surface through the root zone. Since soil in permanently flooded areas can quickly become hypoxic or even anoxic due to biologic activities, flushing of oxygen-depleted ground-water with surface water may deliver and make nutrients available to the root zone for tree use. Pezeshki and Santos (1998) have shown that anaerobic soil conditions decrease photosynthetic rate and decrease biomass in bald cypress and that trees in oxygenated soils grow better.

Davidson *et al.* showed that while there is evidence for a relationship between precipitation and growth, there should also be a relationship between inundation and growth. Davidson *et al.* found that areas that experienced different levels and duration of flooding did not have the same amount of flushing. Inundation, though driven by precipitation, is doing something different than precipitation and could be affecting tree growth in relation to how flooded or well-drained the soil is. Since the earliest studies of bald cypress growth in relation to precipitation [Stahle *et al.*(1985), Young *et al.*(1995), and Chambers (2002)], it has been assumed that trees all experienced the same level of soil saturation and inundation and specific information about water depth has not been recorded.

These studies focus on the initial change and length of inundation but not the fluctuations of inundation. Based on the study by Davidson *et al.*, the duration of inundation might not be as reliable a predictor of growth as the amount of inundation. The fluctuations in inundation could be due to precipitation as Davidson *et al.* suggest or they could be due to changes in stream flow through dam management practices, etc. These studies raise the question of whether growth might show a clearer relationship to the amount of inundation than to the duration of inundation.

On a shorter temporal scale, the relationship between growth and weekly fluctuations in inundation during the growing season was studied by Keeland and Sharitz (1997). While studies done at permanently flooded sites have shown an initial increase in and relationship with growth, Keeland and Sharitz found that growth in trees in saturated (permanently flooded) soils was not related to fluctuations of water level on a weekly scale. Growth in areas where trees were only subjected to periodic, low levels of flooding showed a significant relationship to water level fluctuations (Keeland and Sharitz 1997). The study also raises questions about inundation and growth, specifically, if the location of trees and the exact hydrology of the soil can affect the relationship between growth and inundation.

The objectives of this study were to examine the effects of precipitation and inundation on growth of bald cypress and to distinguish between precipitation effects and inundation effects so that we might be better able to interpret ring width increments in these trees. Two different approaches were used to examine inundation and precipitation effects. One was to examine data from trees that exist at the same general elevation where long term water level and precipitation data exist, so that inundation and precipitation effects could be compared. The other method was to examine tree growth at different elevations within a swamp to see how inundation and precipitation differentially affected those trees.

II. Materials and Methods

Sardis Dam

Sardis Dam is a flood control dam located on the Little Tallahatchie River near Batesville, MS that was opened in 1940 and is operated for management by the U.S. Army Corps of Engineers (Chambers 2002). Tree growth data for eight bald cypress in three locations (Chewalla, Clear, and Blackwater Creeks) above Sardis Dam were collected by Chambers (2002). Precipitation data used by Chambers was obtained from the National Weather Service. An inundation data set was calculated from daily lake level data acquired from the U.S. Army Corps of Engineers. Since Chambers focused on precipitation and the length of time trees above the dam were inundated, her tree-growth data were re-analyzed to determine the relationship of growth to the amount of inundation. The trees above the dam were at elevations of roughly 78 m above sea level. Since the exact location of the trees and the level of soil saturation of the trees was not known, individual tree records were standardized to safeguard against any one tree with extreme values from distorting the analysis. The dam was closed in 1939, but the records for the years 1940-1942 skewed the results of the original analysis, so they were discarded by Chambers and again here. The trees were standardized over the years of 1943-1997, the same period of record used by Chambers. A five-year moving average was calculated for the tree data from 1945-1995 to filter some of the obvious site-specific variation between trees from the three different locations and to ensure that the variation is focused on the inundation effect. The average and standard deviation for each tree's filtered responses were calculated and used to standardize tree growth records for all years. Monthly lake level totals above 260 ft ASL (approximately 78 m) were found and the total lake level for the winter rainy period of January, February, and March were computed as had been done by Chambers for precipitation. The statistical relationship of standardized tree growth to the amount of inundation from January to March was then examined using SAS v. 9.2.

Sky Lake

Sky Lake is an oxbow lake of the Mississippi River system (Galicki 2002) located about 6 miles north of Belzoni, MS. The wetland area around the lake becomes inundated from late fall to early spring. Water levels of the lake edge and surrounding wetland area were recorded with three piezometer nests placed for a study by Davidson *et al.* (2006). The nests were along a north-south transect along the northeast area of the lake and along an elevation gradient with each nest about 0.5 m above the previous nest. Each nest holds six piezometers, at depths of 1, 2, and 3 m; and 0.25, 0.50, and 0.75 m for measuring hydraulic head and water chemistry, respectively. Water level data used for analysis in this study were obtained from these piezometer readings and additional readings from 2006-2009 (Davidson, unpublished data). Daily precipitation data from 1960-2009 for the area were obtained from the Belzoni, MS station of the National Weather Service. Two tree growth data sets from Sky Lake were used. The first data set was obtained by Galicki (2002 and unpublished data) and the second set was obtained by the author for use in this study.

The first tree growth data set from Sky Lake came from Galicki (2002) and additional unpublished data provided by Galicki. Twenty-two bald cypress cored and measured by Galicki in his western study area of Sky Lake were used. An approximate location for each tree is known based on data provided by Galicki, my own survey of the area, and correspondence between some numbered tags placed on trees by Galicki and later also cored for this study (Figure 1). Only measurements from 1960-1996 were used due to the limitation of complete precipitation and tree growth records. The growth measurements of the selected trees were standardized over the period being analyzed using the same method that was used with the Sardis data set.

Forty bald cypress trees were cored at Sky Lake on 29 August 2009. Trees were on a north-south transect close to the piezometer nests (Figure 2). The trees are located along an elevation gradient, with lower elevations near the edge of the open water and higher elevations closer to the road. Each tree was cored from a ladder extending above any buttresses. A single core was obtained from each tree with a 4.3-mm diameter increment borer and placed in a straw to keep them separated and intact. A handheld GPS unit was used to get an exact location for each tree, except for tree number three whose location is inferred based on proximity to the other trees. The cores were taken back to the lab, placed in a fume hood, and allowed to dry for four weeks. Once the cores were completely dried, they were glued to wooden trays. The cores were sanded down, beginning with very coarse (100 grit) sandpaper and moving to fine (600 grit) sandpaper for polishing. Each core was examined under a dissecting microscope that contains a calibrated eyepiece micrometer.

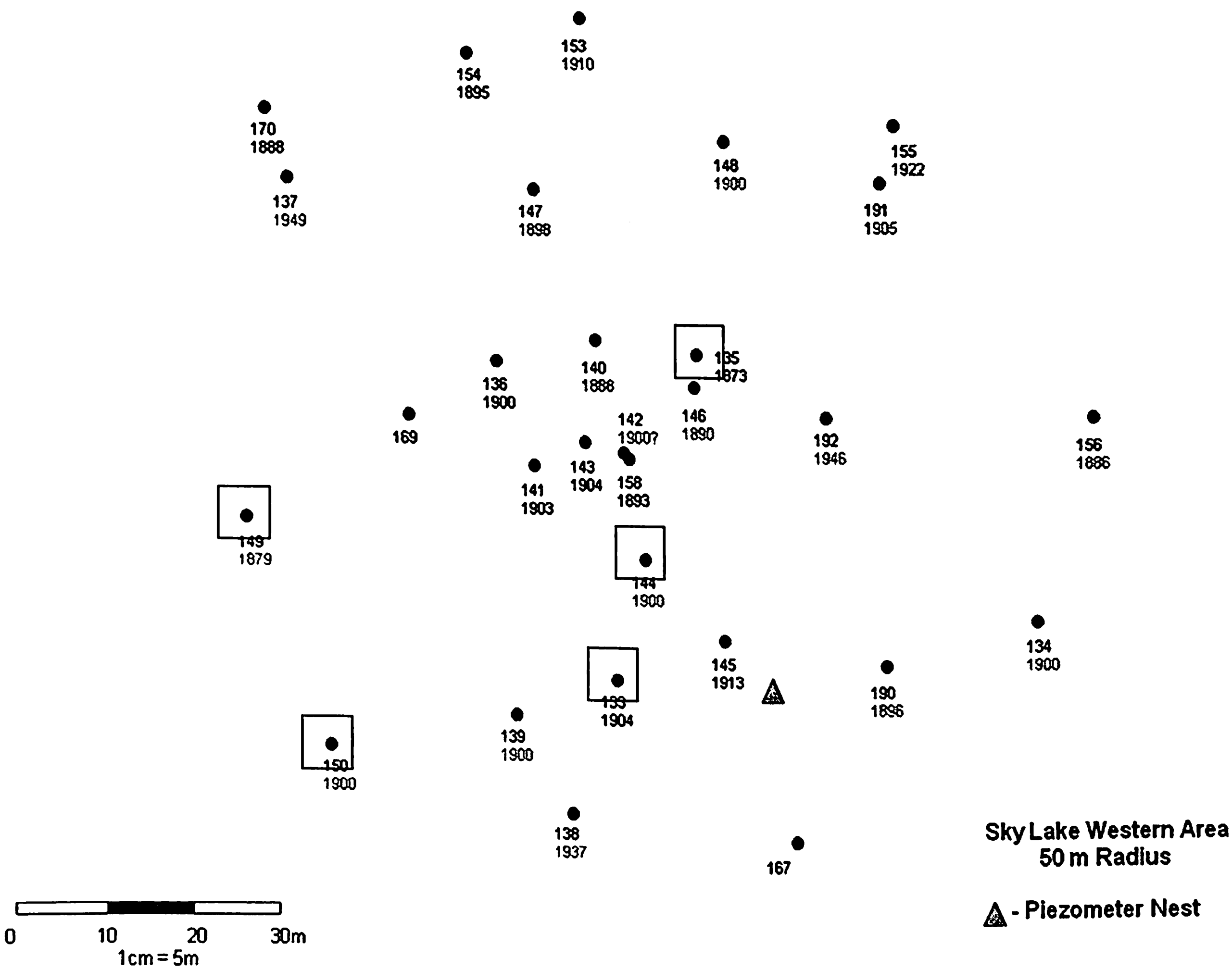

Figure 1: Map of trees cored by Galicki. Piezometer nest shown is nest 2 from Davidson *et al.* (2006) and in Figure 2. Squares indicate trees in the current study and having tags from Galicki's study, so their locations are well known.

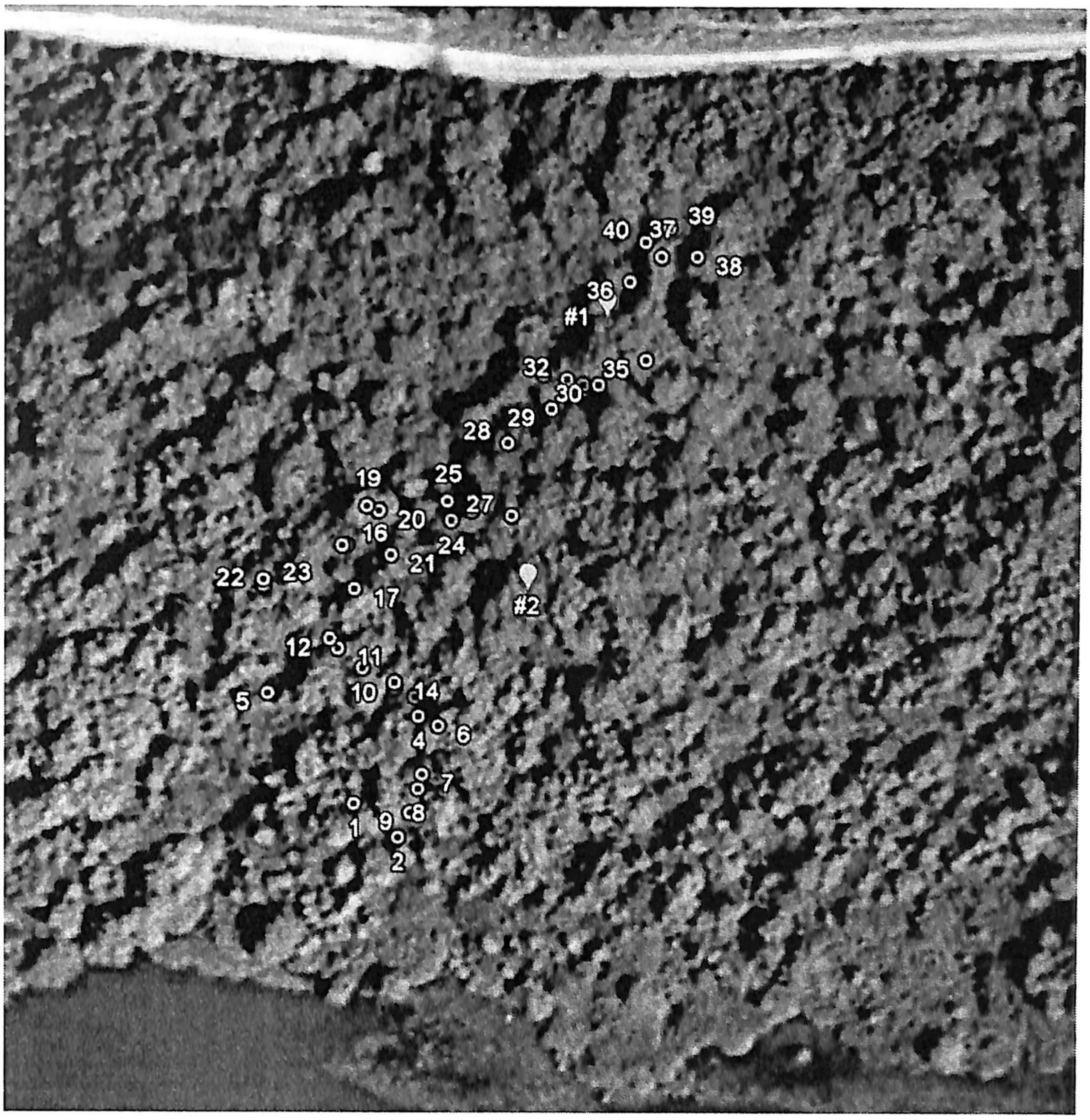

Figure 2: Map of forty trees cored at Sky Lake, wells 1 and 2 are from Davidson *et al.* (2006). Open water is shown at the bottom of the picture and the access road is shown at the top.

The ring widths for the most recent eight years (from 2002-2009) were measured. The raw ring width data were standardized in the same manner as the other two data sets (subtracting the mean growth for each tree from the raw data and dividing by the standard deviation for the ring widths for each tree). The trees were analyzed in five groups based on elevation (Figure 3). The elevations of each tree were not recorded at the time of the coring, but elevations of some trees within each group and the upper two piezometers were recorded on 8 November 2009 when the study site was flooded; elevation was determined by measuring water depth with a plumb bob. Group 1, closest to the open water, had the lowest elevation, with each subsequent group increasing in elevation, and ending with group 5 closest to the road and at the highest elevation. The growth of the trees was then averaged to obtain a mean growth for each group.

Calculations

Since Galicki (2002) found that tree growth had a positive relationship with precipitation, his data were re-analyzed because it was determined that the trees fell along the same elevation gradient as the trees cored for this study. With the longer period of growth and precipitation records, the data was re-examined in light of elevation to gain a finer resolution of the effect of precipitation and elevation on growth. The trees were grouped into three groups based on elevation and each group corresponds to a group of trees in the new data set. There is a group at higher elevation and furthest from the open water

Figure 3: Map of trees at Sky Lake grouped by elevation. Elevation groups are labeled by number with water depth elevations on 8 November 2009, shown.

(corresponding to my group 5), a group at a middle elevation (corresponding to group 4), and a group at lower elevation closest to the open water (corresponding to groups 2 and 3). Ring width measurements were averaged within these three groups. The total amount of precipitation for the January-March growing season was found. The statistical relationship between growth and precipitation was examined using SAS v. 9.2 (SAS Institute, Cary, NC).

The growth data from the forty trees cored for this study were related to both inundation and precipitation. Monthly means of the water level data from Davidson's third nest were calculated from the daily data provided by Davidson (Davidson *et al.* 2006 and unpublished data). The water level at the second nest was then found by subtracting the elevation of the second nest from the water level data from nest three. The elevations of each group relative to nest two were then added to water level data for nest two to obtain the monthly average water level for each group of trees for July 2002 to July 2009. For the months where water level for each group exceeded one meter, the amount over one meter was recorded. For each group of trees the amount of inundation was averaged for January-March (growing season) and for October-April (extended growing season) for each year from 2003 to 2009. Monthly totals of the precipitation data were calculated, and then growing season data and extended growing season levels were averaged and used for analysis. Growth was analyzed with the 2003-2009 precipitation data to directly compare with the inundation data.

III. Results

Re-analysis of Chambers' tree data from Sardis Reservoir

The growth data of trees from above Sardis Dam was originally analyzed in relationship to precipitation and the length of time inundated; although there was a positive relationship to precipitation, tree growth was not related to inundation. I re-examined the growth data from those trees for their relationship to the amount of inundation. Even though the exact elevation of the trees is only known to within 2 m (Chambers 2002), the period of record of growth and inundation is much longer than for the Sky Lake data. The three groups of trees above the dam were found to have no significant relationship to the amount of inundation (Figure 4). Multiple regressions run on the growth data with respect to inundation and precipitation did not yield a significant result for either predictor variable (r^2=0.00086, P=0.9 for both precipitation and inundation).

Re-analysis of Galicki's tree data from Sky Lake

Re-analysis of tree growth data and precipitation data for twenty-two trees cored by Galicki at Sky Lake confirmed a positive relationship between tree growth and precipitation. Each elevation group was positively correlated to precipitation and significantly related ($P < 0.05$) to October to April precipitation (Table 1). The growth of

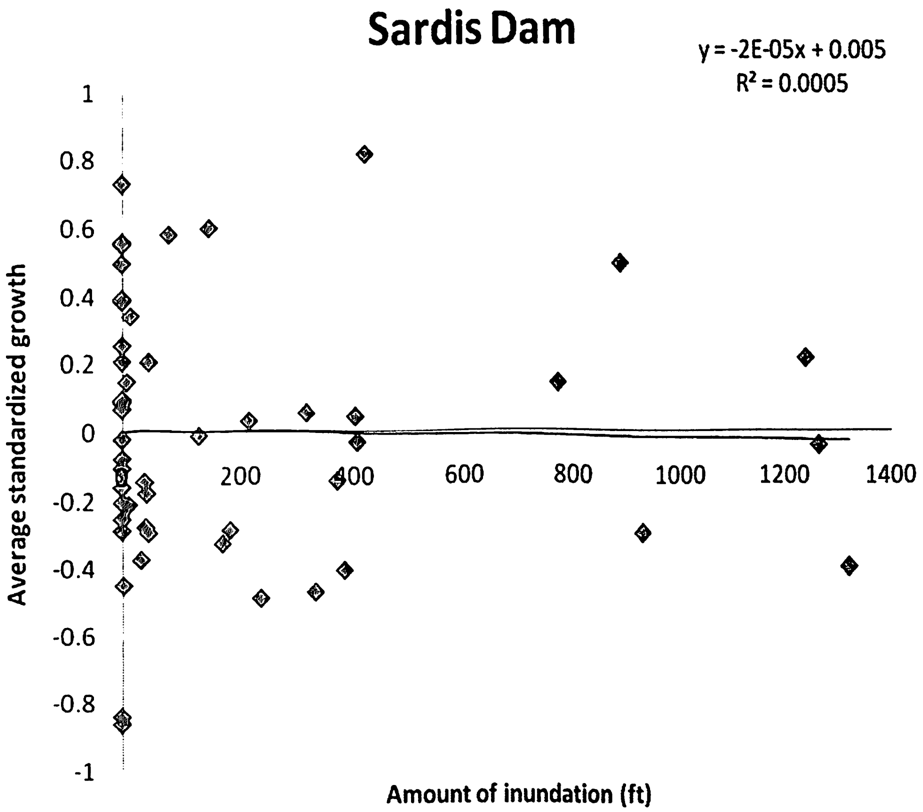

Figure 4: Relationship between growth of trees above Sardis Dam and the amount of inundation (day-ft) from January through March.

Elevation classes	Jan-Mar precip	Oct-Apr precip
Upper elevation trees (n=8)	P= 0.07	P= 0.0044
Middle elevation trees (n=9)	P= 0.097	P= 0.0081
Lower elevation trees (n=5)	P=0.0022	P= 0.0058

Table 1: P values for relationship between growth and Jan-Mar precipitation and Oct-Apr precipitation for Galicki's trees. (n=number of trees)

the trees in each group were related to precipitation, but the slopes of the growth by precipitation relationships were homogenous across elevation classes (P= 0.998).

Analysis of forty new trees from Sky Lake

In the forty trees cored on 29 August 2009 growth varied significantly with precipitation, but differed among groups of trees according to their elevation. The strongest relationship between growth and precipitation was seen in the groups of trees closest to the road, i.e. in groups 4 and 5 (Figure 5). Multiple regression analysis showed that though there was not a significant relationship of growth in a particular group to precipitation, there was a significant difference between groups at the lower elevations (groups 1 and 2 combined) and at the higher elevations (groups 3,4, and 5 combined) in response to both January-March precipitation (P=0.0131) and October-April (P=0.0134).

Analysis of the Sky Lake data showed a positive relationship between growth and inundation that also varied with the elevation of each group of trees. When the growth of

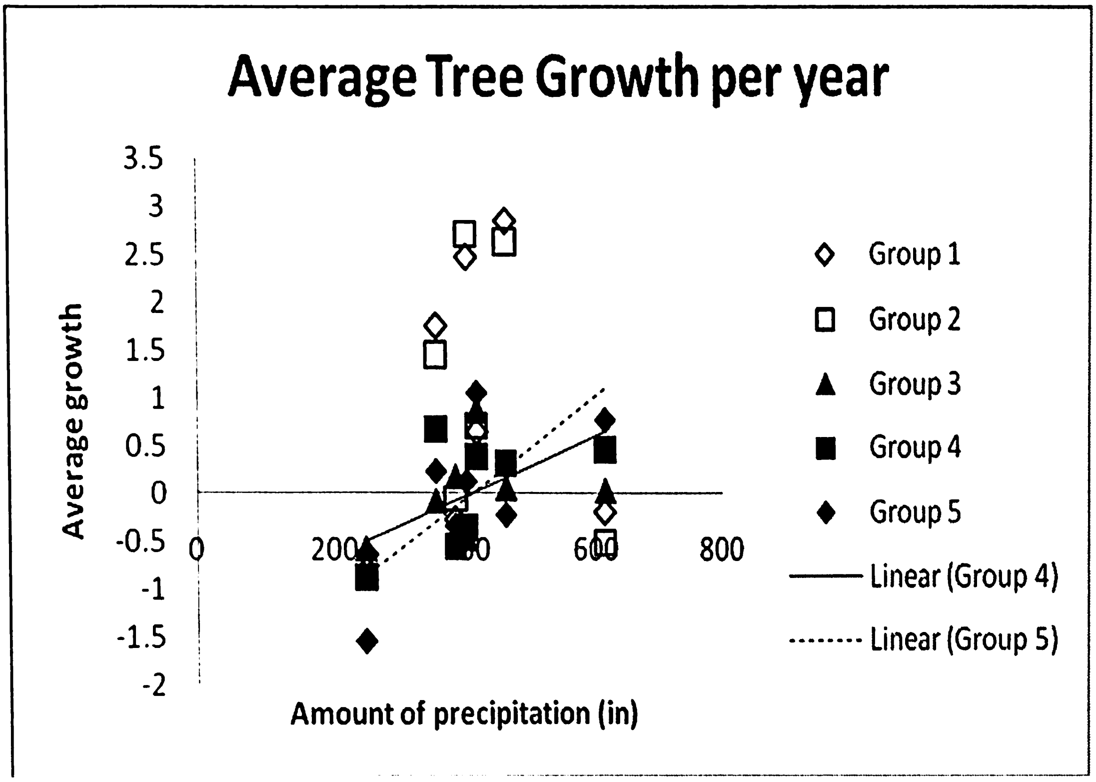

Figure 5: Relationship between growth and precipitation for all trees from Sky Lake. Group 4 and 5 regressions are shown in solid and dotted lines. Group 4: y=0.0031x-1.2738 (r^2=0.345; P= 0.17); Group 5: y= 0. 00529x-2.1667 (r2=0.487; P= 0.081). None of the other tree groups showed a significant relationship between growth and precipitation (all P> .44).

all trees were regressed against inundation, there was not a significant effect of amount of inundation on tree growth (Figure 6). When the trees were grouped by elevation, there were significant relationships of growth to inundation in the lower elevation tree groups 1 and 2 (r^2= 0.575 and 0.608, P=0.048 and 0.038 respectively) but not for trees in groups 3, 4, and 5 (nearer to the road and at higher elevations). The trees closer to water were more influenced by inundation, while the more upland trees closer to the road were influenced by precipitation (Figure 7). Stepwise regression confirmed that for groups 1 and 2 (combined) the inundation effect was highly significant (r^2= 0.69, P=0.0005) while precipitation was not (P=0.37). For groups 3, 4, and 5 combined, the inundation effect was not significant (P= 0.80) while the precipitation effect was significant (r^2=0.32, P=0.01).

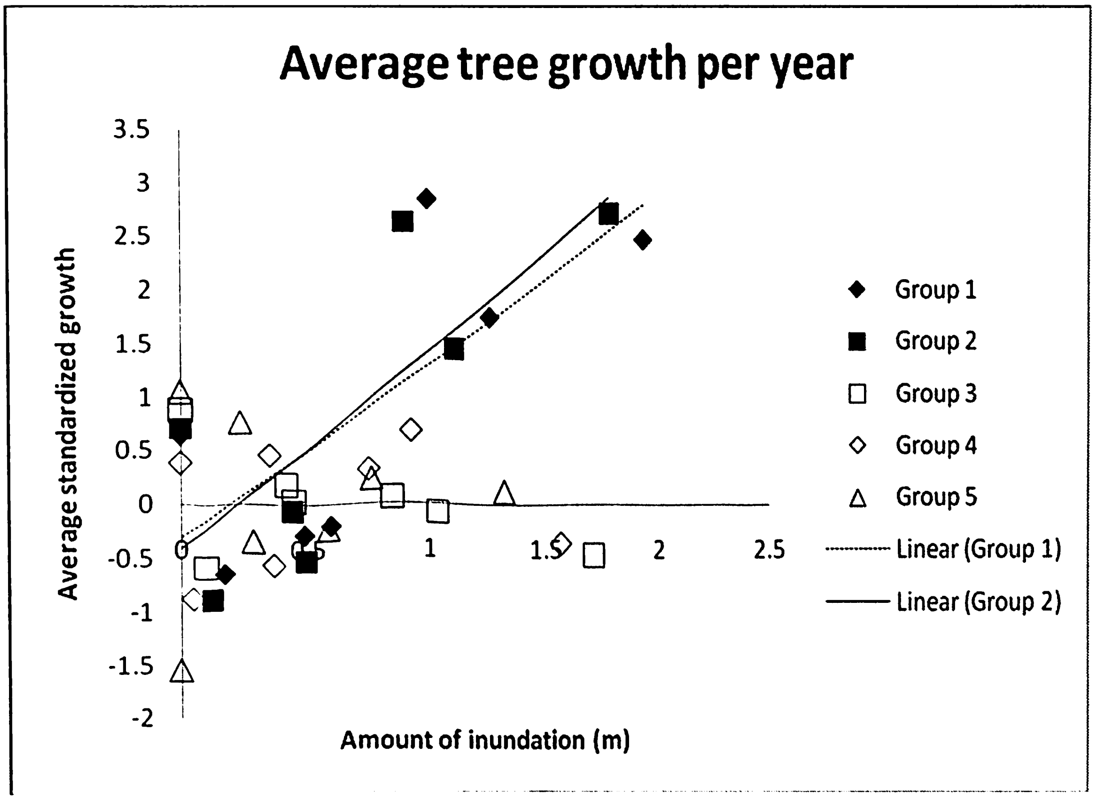

Figure 6: Relationship between growth and amount of inundation for all trees from Sky Lake. Group 1 and 2 regressions are shown in dashed and solid lines. Group 1: y= 1. 5986x-0.3075 (r2=0.575 P=0.048); Group 2: y=1.8297-0.4058 (r^2=0.608 P=0.038). None of the other tree groups showed a significant relationship between growth and inundation (all P >0.14).

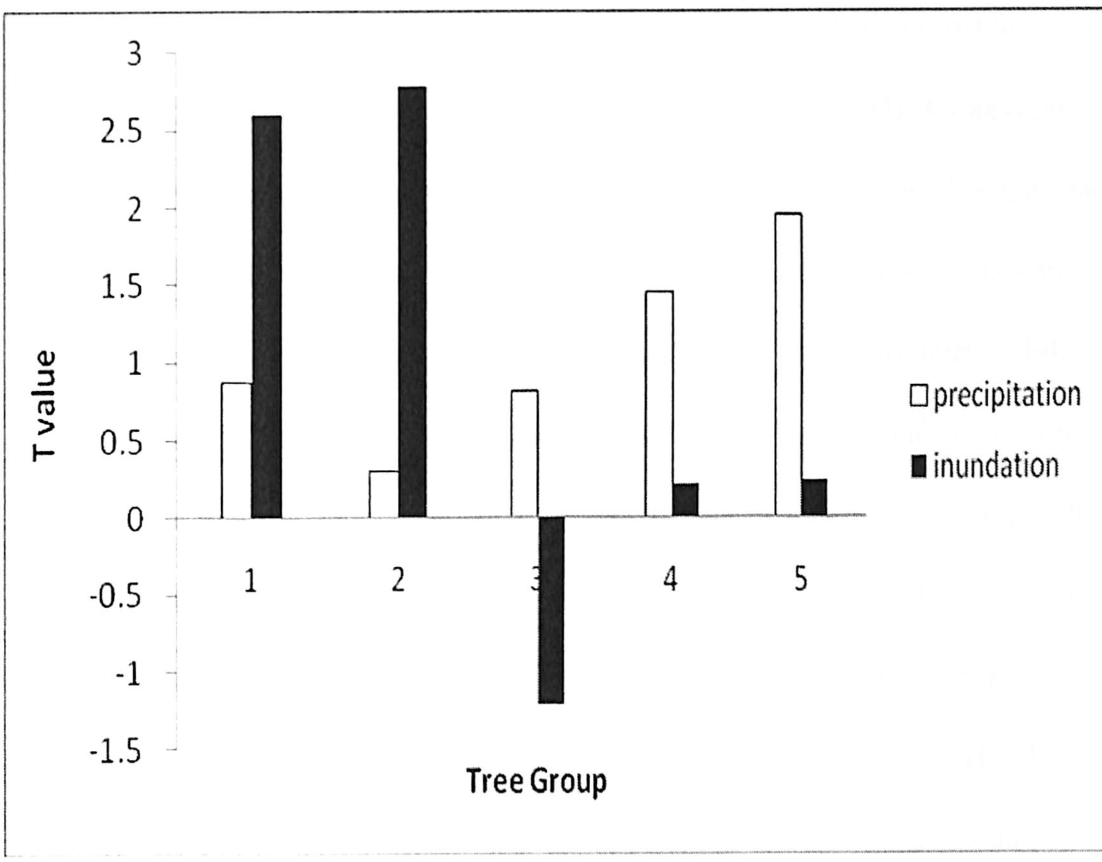

Figure 7: T values of the relationships between precipitation, inundation, and tree growth for all five tree groups.

IV. Discussion

While bald cypress can grow well in flooded areas, their distribution is not limited to swamps and wetlands (Penfound 1952, Mistch and Gosselink 1993). Cypress can grow in stream channels where precipitation is the sole determinate of water depth, on banks and in floodplains where there is periodic flooding, and in uplands where they are rarely, if ever, flooded. The response of the trees in Sky Lake indicates that trees in different areas respond differently to inundation or precipitation. Previous studies conducted with bald cypress and the data presented here have shown a relationship between growth and precipitation because precipitation is a major growth factor for those trees on stream banks and lake edges and those trees that are inundated. Precipitation can affect inundation in a stream channel, where the height of the water is directly related to it, and occasionally out in the floodplain too. Since precipitation was a good indicator of growth, many studies just did not look at inundation as a separate factor.

Based on the data from Sky Lake, the location of the trees in relation to the stream channel affects the relationships between precipitation and growth and inundation and growth. For trees in Sky Lake that are continuously inundated or in soils that are continuously saturated, there is a strong effect of inundation. Soil that is continuously saturated probably becomes anoxic over time leaving trees in inundated soil with little oxygen and nutrients unavailable for growth. Once a certain water depth is reached, the anoxic water is replaced by the fresher oxygenated surface water, resulting in better tree growth. Trees in soils that are well-drained and not subject to long periods of standing water do not respond to inundation in the same way. For these trees the variation in precipitation works better to predict growth and short periods of inundation probably stifle growth instead of stimulating it. For trees in well-drained soils, there is less time for the soil to become anoxic and no benefit of flushing by increased inundation.

Seeing how the trees in different locations responded to precipitation and inundation, it would be beneficial to go back to earlier studies of bald cypress growth and collect samples from trees in different parts of the stream channel that experience different amounts of inundation. With better information on tree location (as needed in the Sardis dam data) and a long precipitation record, we could see if the growth by precipitation relationship that has been observed changes with the location of the trees.

We don't know exactly why the trees in different areas respond as they do. Keeley (1979) found that *Nyssa sylvatica* (the gum tree) in different locations—upland with little inundation, floodplain with intermittent flooding, and swamps with continuous flooding, had different physiological adaptations to flooding. The roots of the upland trees weakened under flooded conditions and had poor survival rates after a year of flooding, the roots of the swamp trees grew newer, larger roots that could tolerate alcoholic fermentation initially and eventually received an increase of oxygen, and the roots of floodplain trees also grew new roots and increased oxygen to the root zone but they also behaved like upland trees when in drained conditions (Keeley 1979). The trees from different locations had different adaptations that allowed them to grow well in their respective locations (dry, semi-flooded, and continuously flooded).

Bald cypress could be responding to environmental conditions in a similar way. One well-known adaptation that bald cypress could be using in response to flooding are cypress knees. Cypress knees are structures thought to be a means of either facilitating gas exchange or serving as structural support for trees in flooded areas (Mitsch and Gosselink 1993). According to Penfound (1952), if the knees are special adaptations for gas exchange then they should be most beneficial for trees in deep water. Penfound (1952, p. 419) states "...cypress does not produce 'knees' on unflooded lands or on soils inundated with water continuously but only on land which is subject to alternate flooding and draining. Cypress 'knees' are absent, therefore, where presumably most needed—in deep water...it is doubtful that cypress 'knees' are of any great value in respiratory exchange." Based on the well data of Davidson *et al.* and the elevation dependent growth relationships in Sky Lake bald cypress, trees in deeper water would not need knees because they are receiving oxygen through increased inundation (oxygen exchange through groundwater flushing) and upland trees are in soil that does not become anoxic.

When there is a permanent or major change in the hydrology of an area, the predictable relationship between growth and interannual variation in precipitation might also change. Studies done in areas with a hydrologic change show trees usually have a multiple year response. Changes that result in an increase in inundation such as an earthquake (Stahle *et al.*, 1992) or road construction (Young *et al.*, 1994) cause short term increases in tree growth and changes that result in a change in inundation such as dam construction (Chambers, 2002) or stream incision (Valentine *et al.*, 1997) cause the relationship between growth and precipitation to break down. As the short-term growth responses of bald cypress to hydrologic changes beyond interannual variation in precipitation are unpredictable and varied and rarely studied, the long-term responses of trees to alterations in the frequency of either inundation or drought are not known. The long-term responses may be especially important in future reconstructions of climate based on these long-lived trees. The extent to which the responses are unknown will make climate reconstruction problematic. Whenever the flooding regime changes, it could take many years for the trees in an area to adapt, making it difficult for future studies to accurately model past climates in the absence of detailed knowledge of landscape hydrological history.

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